A Reliability Model for Ni-$BaTiO_3$-Based (BME) Ceramic Capacitors

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Acronyms

AEC-Q200	Automotive Electronics Council-Q200 (AEC-Q200)
BME	Base-Metal Electrodes (BMES)
CA	Construction analysis (CA)
CARTS	Capacitor and Resistor Technology Symposium (CARTS)
DPA	Destructive Physical Analysis (DPA)
GSFC	Goddard Space Flight Center (GSFC)
MLCCs	Multi-Layer Ceramic Capacitors (MLCCs)
MTTF	Mean Time to Failure (MTTF)
SCDs	Specification Control Drawings (SCDs)
TTF	Time to Failure (TTF)

Outline

- General expression of reliability for ceramic capacitors with base-metal electrodes (BMEs)
  - Statistical model
  - Acceleration functions
    - Catastrophic: Power-law (Prokopowicz and Vaskas)
    - Slow degradation: Exponential
- Improved reliability model of BME ceramic capacitors
  - Impact of grain size
  - Impact of dielectric thickness
  - Impact of number of dielectric layers
  - Impact of chip size
  - General reliability model
- Application example(s)
- Summary and future work

A General Expression of Reliability for MLCCs

$$\boxed{R(t) = \varphi(N, d, \bar{r}, S) \times AF(V, T) \times \gamma(t)}$$

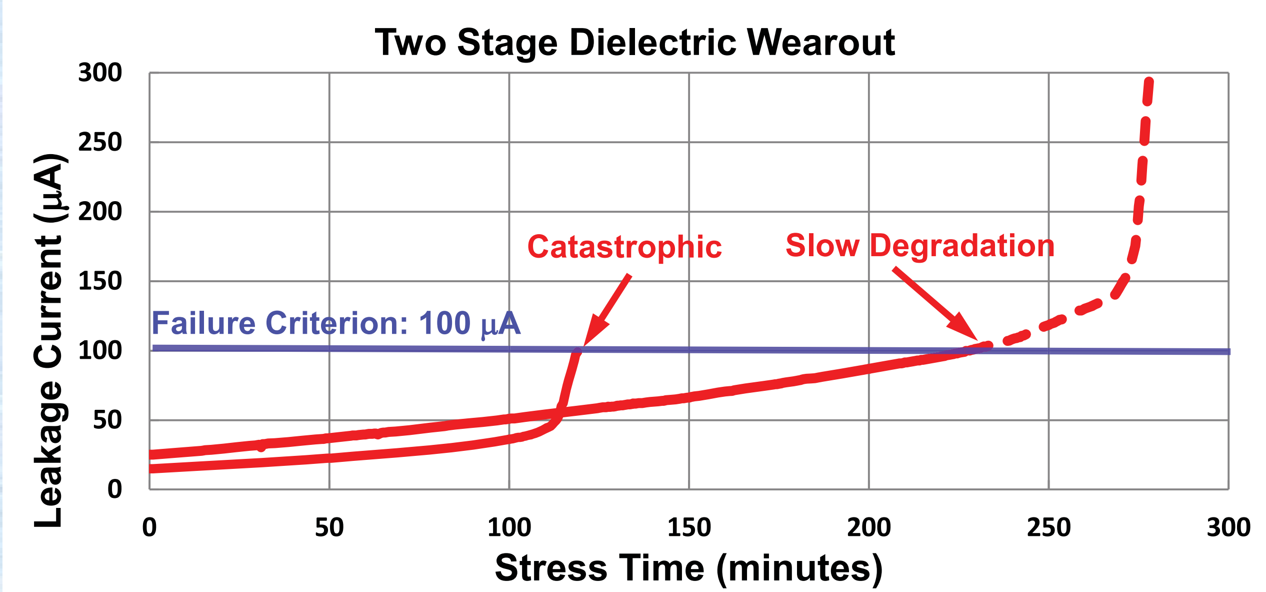
$\gamma(t)$: Statistical distribution that describes the *individual variation* of properties (Weibull, log normal, normal)

$AF(V, T)$: Function that describes the lifetime of a device in response to external stresses (*independent of individual units*)

$\varphi(N, d, \bar{a}, S)$: Effects due to the characteristics of a capacitor device (structure, construction, etc.)

- Statistical distribution:
  - 2-parameter Weibull: $\gamma(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$
  - A function of time; always decreases with time
  - Probability of a failure occurring: $\gamma(t) = [0, 1]$
  - Durability of an MLCC that can function normally during wearout:
    - When β >3 and $t < \eta$, $R(t) \sim 1$, a reliable life span before η
    - When β >3 and $t > \eta$, $R(t) \sim 0$, parts failed rapidly after η

Determination of Acceleration Functions (Cont'd)



- A two-stage dielectric wearout failure mode is better for describing the failure behavior in BME MLCCs with $BaTiO_3$ dielectrics (*supported by recent failure analysis results*)
  - *Slow degradation*: leakage increases with time nearly linearly due to oxygen vacancy migration until the failure criterion (100 μA) is reached (parts failed prior to catastrophic failure)
  - *Catastrophic failure*: leakage increases gradually, followed by time-accelerating catastrophic failures

Determination of Acceleration Functions (Cont'd)

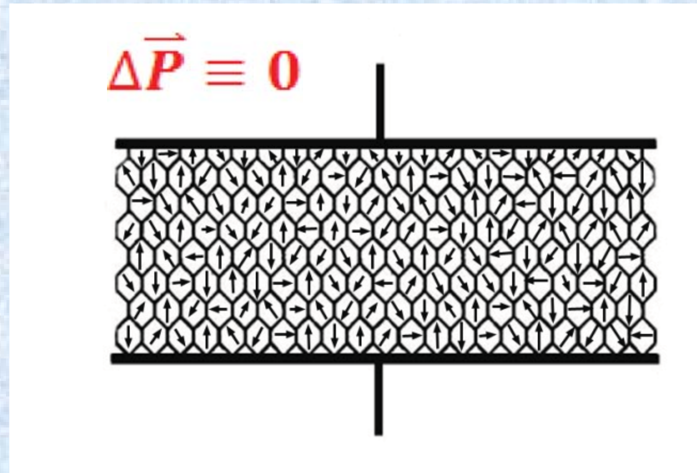
- Previous studies have shown that for the two different failure modes, the acceleration functions appear to be different
  - D. Liu, "Highly Accelerated Life Stress Testing (HALST) of Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, Houston, TX, pp. 235–248, (March 26–29, 2013)
  - R. Weachock and D. Liu, "Failure Analysis of Dielectric Breakdowns in Base-Metal Electrode Multilayer Ceramic Capacitors," *CARTS Proceedings*, Houston, TX, pp. 151–165, (2013)
  - J. W. McPherson, ***Reliability Physics and Engineering: Time-to-Failure Modeling*** (Springer, New York, 2010)
  - N. Kubodera, T. Oguni, M. Matsuda, H. Wada, N. Inoue, and T. Nakarama, "Study of the Long Term Reliability for MLCCs," *CARTS Proceedings*, p. 77, (2012)

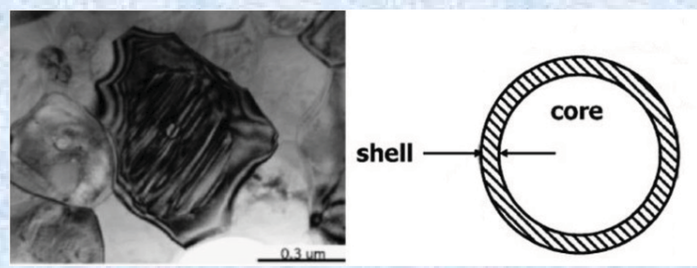
- *Catastrophic* failures fit power-law (*P-V equation*): $$\frac{MTTF_1}{MTTF_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

- *Slow degradation* failures fit exponential-law: $$\frac{MTTF_1}{MTTF_2} = exp[-b(E_1 - E_2)]exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

Improved Reliability Model of BME Capacitors
I. Ceramic Grain Structure of BME Capacitors with $BaTiO_3$

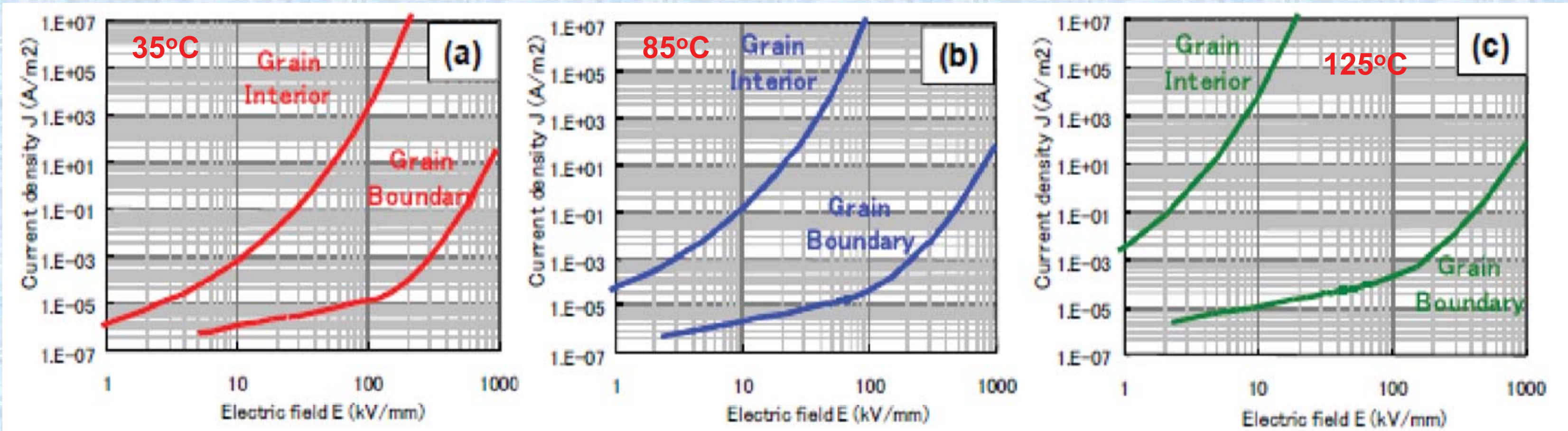
- Ceramic is a polycrystalline structure that contains a large number of closely packed single-crystal *grains*
- The microstructure of each grain is inhomogeneous; a core-shell structure is often reported due to the inhomogeneity between a grain boundary and the interior of a grain
  - Core: ferroelectric $BaTiO_3$ single crystal
  - Shell: non-ferroelectric, different composition and structure





Improved Reliability Model of BME Capacitors

II. Inhomogeneous Resistivity of BME Capacitors with $BaTiO_3$



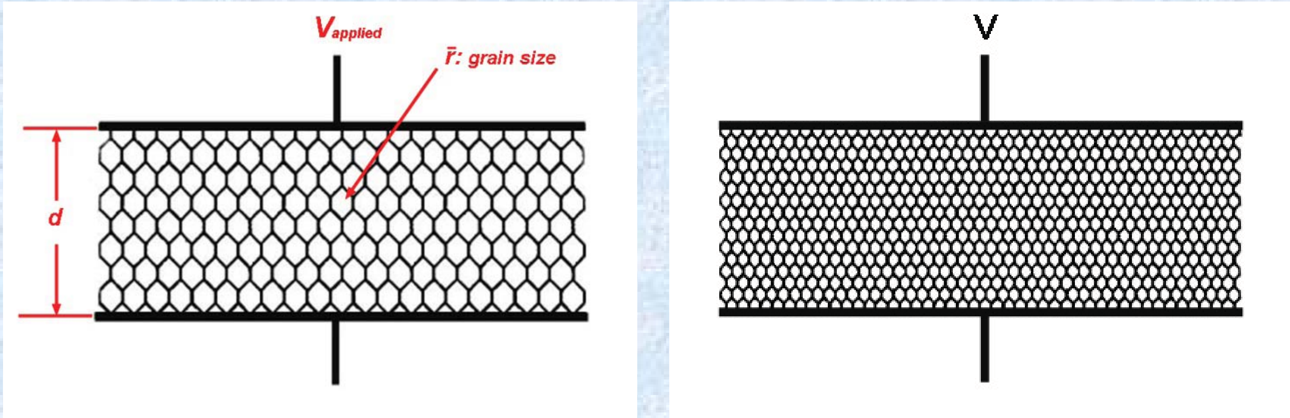
ICC3: Symposium 6: Advances in Electro Ceramics

IOP Conf. Series: Materials Science and Engineering **18** (2011) 092007

- Resistivity is significantly different between grain interior and grain boundary
  - ➢ Core is relatively conductive; shell is highly resistive (bearing the insulating resistance (IR) for a $BaTiO_3$ grain)
  - ➢ Applied voltage distribution is inhomogeneous
  - ➢ Due to the formation of a highly **insulating** layer at the grain boundary, most of the voltage will be applied on the grain boundary region

Improved Reliability Model of BME Capacitors

III. Impact of Grain Size



- When applied voltage and dielectric thickness are identical for two capacitors, the one with the smaller grain size has a better dielectric strength
- For this reason, powders with smaller particle sizes are always preferred for making BME capacitors
- Voltage per grain is the key for characterizing the voltage robustness in $BaTiO_3$

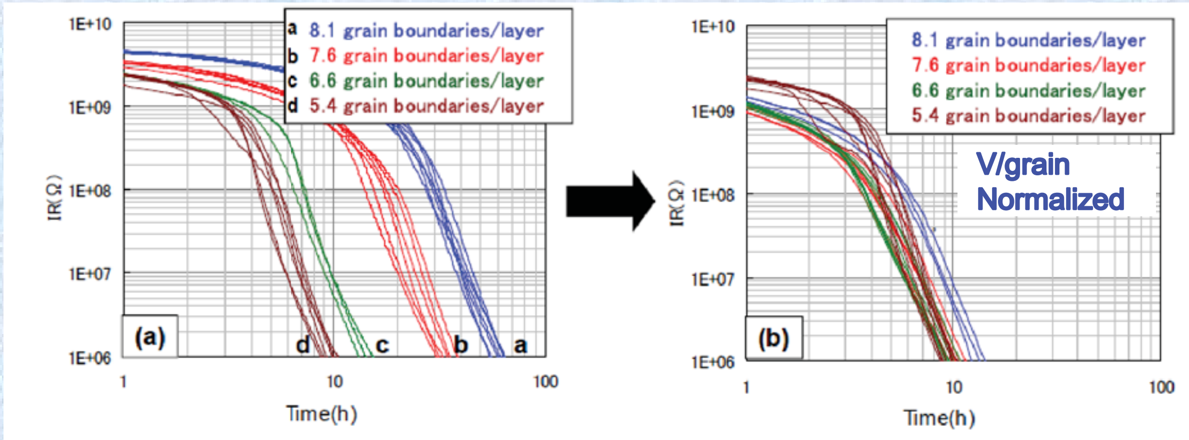
$$\boxed{\text{Voltage Per Grain} = V_{grain} = \frac{V_{applied}}{\left(\frac{d}{\bar{r}}\right)} = V_{applied} \times \left(\frac{\bar{r}}{d}\right)}$$

$\bar{r}$: average grain size (μm)
d : dielectric thickness (μm)

$\left(\frac{\bar{r}}{d}\right)$ A key structural parameter that determines the dielectric strength and reliability!

Improved Reliability Model of BME Capacitors

III. Impact of Grain Size (Cont'd)



- Mean-time-to-failure (MTTF) data as a function of number of grains per dielectric layer has been measured at 150°C and 10 KV/mm
  - ➢ The more grains per dielectric layer, the longer the MTTF
  - ➢ When voltage per grain is normalized to a constant value, MTTF data are identical to a single grain

Prokopowicz and Vaskas equation: $$MTTF = \frac{C}{V^n} \cdot e^{\left(\frac{E_a}{kT}\right)}$$

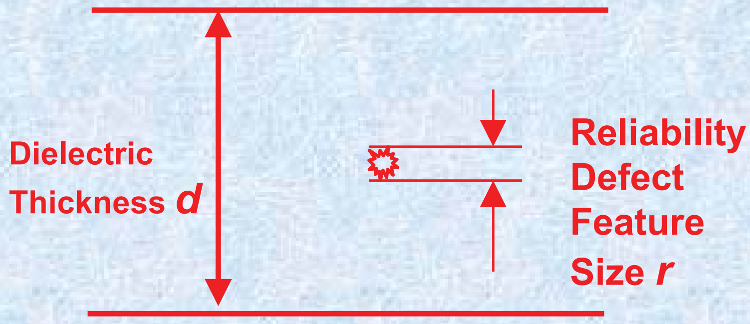
At a given temperature: $$MTTF = \frac{c}{V_{grain}{}^{n}} = \frac{c}{\left[\frac{V_{applied}}{\left(\frac{d}{\bar{r}}\right)}\right]^n} = \frac{c}{V_{applied}{}^{n}} \times \left(\frac{d}{\bar{r}}\right)^n$$

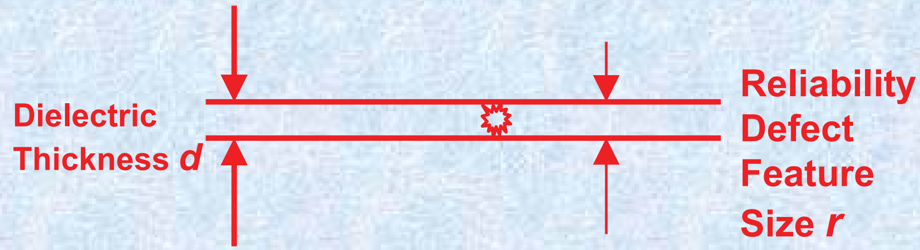
Improved Reliability Model of BME Capacitors
IV. Impact of Reliability Defects

- Reliability failures are caused by reliability defects
- Quality defects and reliability defects:
  - **Quality defects:** currently deficient products or components, particularly ones that are out of the standard specifications. Quality is generally expressed in percentages.
  - **Reliability defects:** failures that might occur in the future inside a product that has been working well so far. Reliability must therefore be regarded as a ratio expressed in terms of units of time.
- Reliability defects may behave in two ways:
  - They can be benign for the rest of the product life and not cause a failure
  - They can be catastrophic, depending on the feature size and the level of external stress
- Increasing the external stress level is equivalent to:
  - Increasing the applied voltage for a given dielectric thickness
  - Decreasing the dielectric thickness at a constant voltage

Improved Reliability Model of BME Capacitors

IV. Impact of Reliability Defects (Cont'd)





Dielectric layer reliability: $R_i(t) \to 1, when\ d \gg r; R_i(t) \to 0, when\ d \approx r.$

For Weibull model: $$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \cdot \left[1 - \left(\frac{r}{d}\right)^{\xi}\right]$$

Since: $r \approx c \times \bar{r}, \quad \bar{r}\ is\ the\ average\ grain\ size$

We have: $$P = \left[1 - \left(\frac{r}{d}\right)^{\xi}\right] = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right], \quad (\alpha \geq 5)$$

***P* is a geometric factor that determines the dielectric reliability with respect to the microstructure of an MLCC.**

Improved Reliability Model of BME Capacitors

IV. Impact of Reliability Defects (Cont'd)

With external stress: $$\eta(V,T) = \frac{C}{V^n} \cdot e^{-\frac{E_a}{kT}}$$

We have: $$R_i(t) = R_w(t) \cdot \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right] = e^{-\left[\frac{t}{C} \cdot V^n \cdot e^{\frac{E_a}{kT}}\right]^{\beta}} \cdot \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right], \alpha \geq 5$$

In general: $$R_w(t \leq \eta) = e^{-\left[\frac{t}{C} \cdot V^n \cdot e^{\frac{E_a}{kT}}\right]^{\beta}} = 1$$

So finally, *single-layer dielectric reliability* can be simplified as:

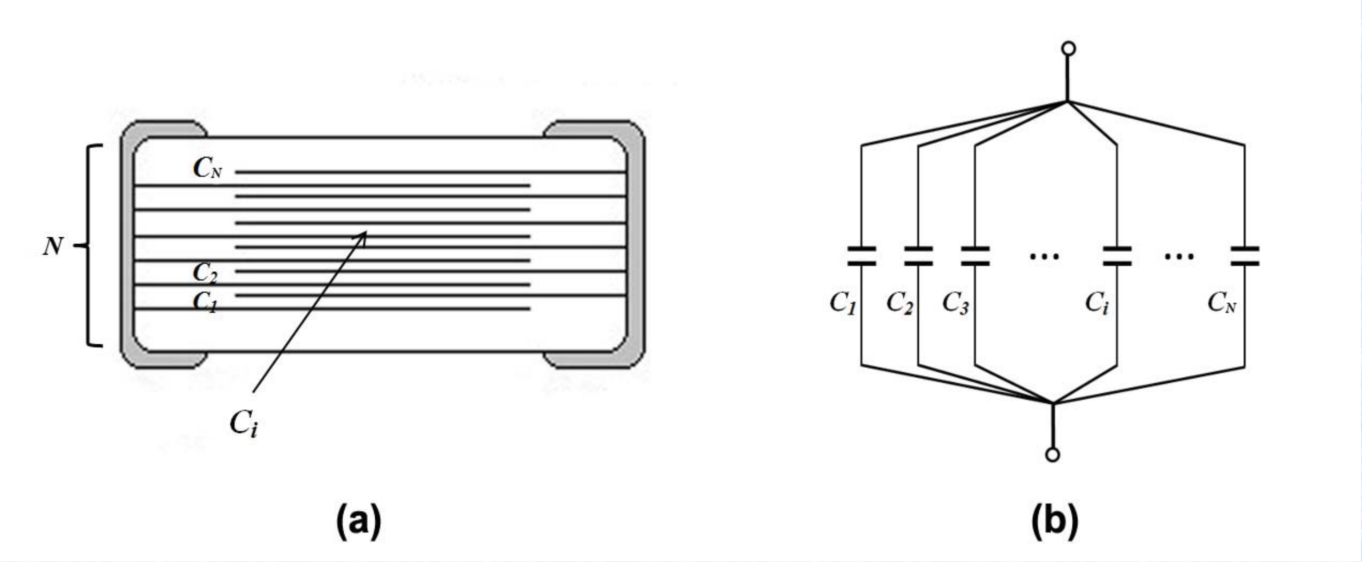
$$R_i(t \leq \eta) \approx \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]$$

α is an empirical constant that depends on the processing conditions and microstructure of a ceramic capacitor.

α ≈ 6 (V ≤ 50) and α ≈ 5 (V >50) for BME MLCCs

α ≈ 5 for most PME MLCCs

Improved Reliability Model of BME Capacitors
V. Impact of Number of Dielectric Layers



Total capacitance: $C_t = C_1 + C_2 + C_3 \ldots + C_i \ldots + C_N = N \cdot C_i$

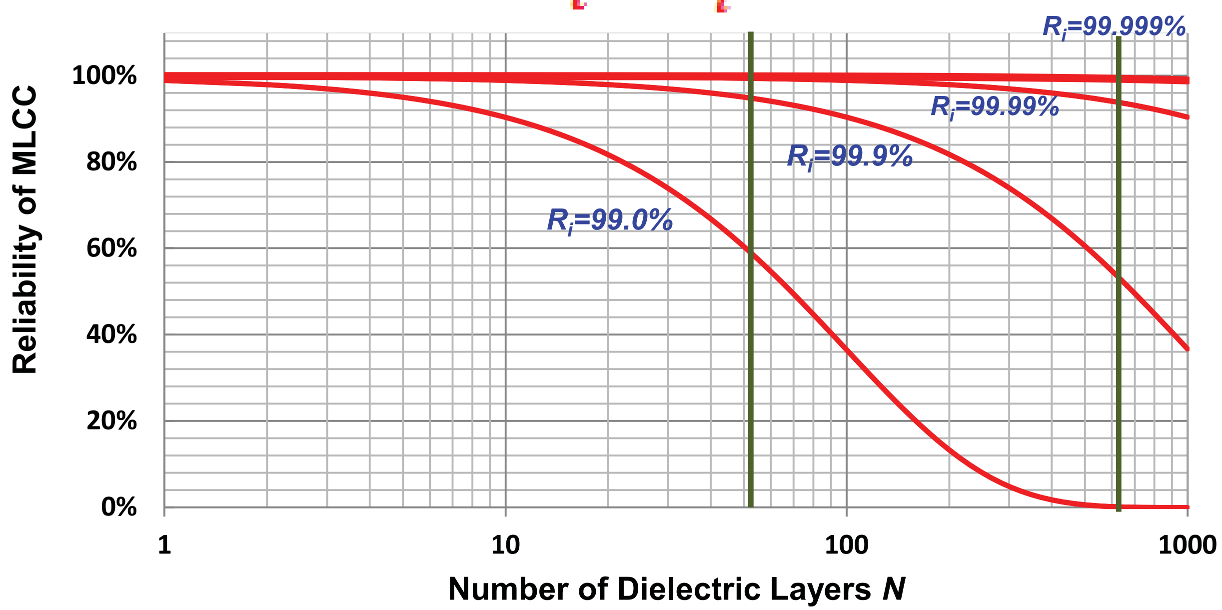
Total reliability: $R_t = R_1 \times R_2 \times R_3 \ldots \times R_i \ldots \times R_N = R_i^N$

$R_i(t)$: Single dielectric layer reliability, as discussed earlier

Improved Reliability Model of BME Capacitors

V. Impact of Number of Dielectric Layers (Cont'd)

$$R_t = R_i^N$$



- The reliability of an MLCC R_t decreases with increasing *N*
- The value of *N* can be as high as 1000!

$$\varphi(N, d, \bar{r}, S) = R_t(t < \eta) = R_i(t < \eta)^N = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^N, \qquad (\alpha \geq 5)$$

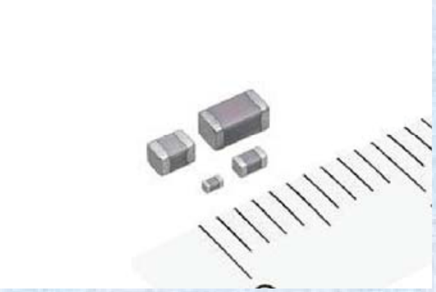
Improved Reliability Model of BME Capacitors

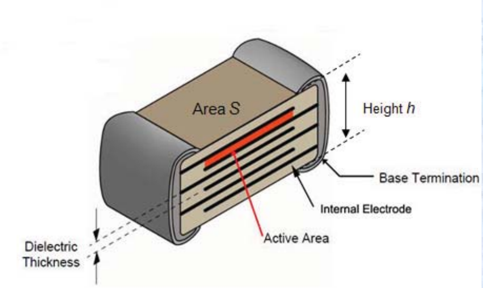
VI. Impact of Capacitor Chip Size (Cont'd)

Chip Size	Length (μm)	Width (μm)	Terminal-t (μm)	Side margin (μm)	End margin (μm)	Effective area (mm^2)	Chip size scaling factor *S*
0402	1000 ± 100	500 ± 100	250 ± 150	125	100	0.225	1.00
0603	1600 ± 150	810 ± 150	350 ± 150	175	100	0.763	3.39
0805	2010 ± 200	1250 ± 200	500 ± 200	250	150	1.520	6.76
1206	3200 ± 200	1600 ± 200	500 ± 200	250	150	3.510	15.60
1210	3200 ± 200	2500 ± 200	500 ± 200	250	150	5.940	26.40
1812	4500 ± 300	3200 ± 200	610 ± 300	300	200	10.920	48.53
2220	5700 ± 400	5000 ± 400	640 ± 390	320	220	23.074	102.55
1825	4500 ± 300	6400 ± 400	610 ± 360	300	220	23.244	103.31

- Effective chip size 0805 is equal to 6.76 size 0402 MLCCs connected in parallel
- Reliability: $R_i(0805) = R_i(0402)^{6.76}$
- In general:

$$R_i(xy) = R_i(0402)^S$$

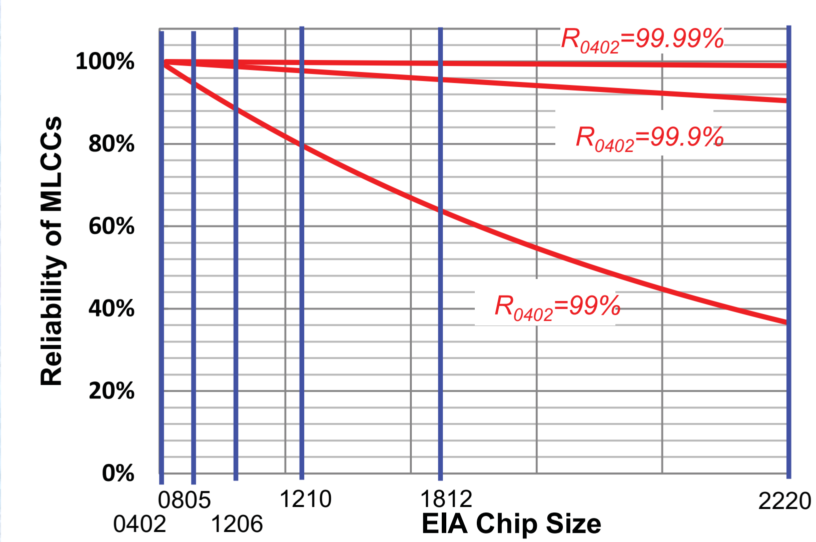




- Where ***S*** is the MLCC *chip size scaling factor* with respect to the chip size of an 0402 MLCC; *xy* is the EIA chip size, R_i is the reliability of a single dielectric layer

Improved Reliability Model of BME Capacitors
VI. Impact of Capacitor Chip Size (Cont'd)

- The reliability of MLCCs decreases with increasing chip size, but not significantly
- When the chip *size scaling factor* increases by a hundredfold, the reliability declines:
  - 45% when $R_i(0402) = 99\%$
  - 10% when $R_i(0402) = 99.9\%$
  - 1% when $R_i(0402) = 99.99\%$



- The reliability of a MLCC with chip size ***xy*** *and* $\boldsymbol{N_{xy}}$ layers of dielectric $R_t(xy)$ can be expressed as:

$$R_t(xy) = R_i(xy)^{N_{xy}}$$

Since: $$R_t(0402) = R_i(0402)^{N_{0402}}$$

One finally has: $$R_t(xy) = \left[R_i(0402)^{N_{xy}}\right]^S = \left[R_t(0402)^{\frac{N_{xy}}{N_{0402}}}\right]^S$$

Improved Reliability Model of BME Capacitors

VI. Impact of Capacitor Chip Size (Cont'd)

- Reliability as a function of chip size:
  Since: $N_{0402} \approx$ ***70-80;*** and: $N_{1825} \approx$ ***280-300, S=100;***

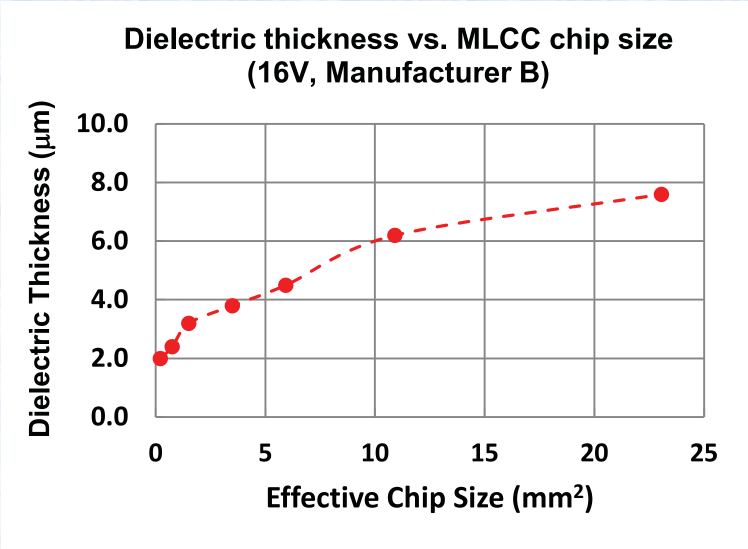
$$R_t(1825) = \left[R_t(0402)^{\frac{N_{xy}}{N_{0402}}}\right]^S = R_t(0402)^{(3\sim4)\times100}$$

- On the other hand, the dielectric thickness ***d*** also gradually increases with MLCC chip size, as shown in the plot below:

- Since the reliability of an MLCC follows a power-law increase with increasing dielectric thickness, one has:

$$\frac{MTTF(1825)}{MTTF(0402)} = \left(\frac{d_{1825}}{d_{0402}}\right)^n = \left(\frac{7.8}{2.0}\right)^{3\sim5} \approx 56\sim902$$

- The reliability decrease due to increasing chip size has been "compensated."
- *Aspect ratio (d / chip size) is the KEY!* The same design rule applies to CMOS gate capacitors.



A General Reliability Model of BME Capacitors

$$R(t) = \varphi(N, d, \bar{r}, S) \times AF(V, T) \times \gamma(t)$$

$$= \left[\mathbf{1} - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} \times \left\{ p \times e^{-\left[\frac{t}{\frac{c}{V_{applied}{}^{n}} \times \left(\frac{d}{\bar{r}}\right)^{n} \cdot e^{\left(\frac{E_{a1}}{kT}\right)}}\right]^{\beta_1}} + (\mathbf{1} - p) \times e^{-\left[\frac{K_0 t}{Ce^{-bE} \cdot e^{\left(\frac{E_k}{kT}\right)}}\right]^{\beta_2}} \right\}$$

Where:

d: dielectric thickness

$\bar{r}$: average grain size

N: number of dielectric layers

α: empirical constant

E: applied electric field

$K_o e^{-\frac{E_k}{kT}}$: degradation rate constant of $V_O^{\cdot\cdot}$

n: power law constant

C, c, and b: constants

p, β_1, and E_{a1}: percentage, Weibull slope constant, and activation energy for failure mode 1: catastrophic failure

Application Example(s): *R (t=0)*

- When t=0, one has

$$R(t=\mathbf{0}) = \left[\mathbf{1} - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}$$

- The initial reliability is only determined by the construction/processing parameters
- This also indicates that high-reliability MLCCs must be built for that; one cannot improve capacitor reliability by “up-screening”
- It has been noticed that if *R(t=0)* is met

$$\boldsymbol{R(t=0)} = \left[\mathbf{1} - \left(\frac{\bar{\boldsymbol{r}}}{\boldsymbol{d}}\right)^{\boldsymbol{\alpha}}\right]^{\boldsymbol{N}} = \mathbf{1.00000}$$

most of commercial BME capacitors would pass Group B life testing per MIL-PRF-55681

Application Example(s): *R (t=0)* (Cont'd)

Testing Results

CAP ID	Grain Size (μm)	Dielectric Thickness(μm)	No. of Dielectric layers N	Calculated R_t	life testing at 2XVr, 125°C 1000 hours	4000 hours
A08X22525	0.305	3.89	211	0.99995	Fail	
B08X33425	0.420	5.80	74	0.99999	Pass	Pass
A08X15425	0.460	9.80	43	1.00000	Pass	Pass
C06X10525	0.440	3.20	150	0.99899	Fail	
A06X10425	0.470	7.89	62	1.00000	Pass	Pass
A12X47425	0.492	10.40	58	1.00000	Pass	Fail
C04X47325	0.386	4.40	60	0.99997	Fail	
B12X47525	0.376	4.34	260	0.99989	Fail	
P08X10425	0.790	20.20	23	1.00000	Pass	Pass
B06X10516	0.273	2.29	179	0.99948	Fail	
A08X47416	0.319	3.75	208	0.99992	Fail	
B12X68416	0.375	6.21	64	1.00000	Pass	Pass
C08X22516	0.224	3.81	212	0.99999	Pass	Fail
B08X22516	0.340	3.23	230	0.99969	Fail	
B08X56416	0.373	4.21	80	0.99996	Pass	
C08X47516	0.230	2.49	260	0.99984	Pass	Fail
B12X10516	0.475	7.82	99	1.00000	Pass	Pass
B04X10416	0.342	3.05	67	0.99987	Fail	
B12X10606	0.365	3.11	348	0.99908	Fail	
B04X10406	0.323	2.50	70	0.99967	Fail	
B08X22506	0.419	3.42	230	0.99922	Fail	
A08X10406	0.490	12.50	34	1.00000	Pass	Pass
B06X22406	0.373	4.01	67	0.99996	Pass	Fail
P06X10405	0.770	12.60	24	1.00000	Pass	Pass

$$R(t=0) = \left[1 - \left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N} = 1.00000$$

- Some commercial BMEs passed the life test; the life testing is still in progress!
- All of Automotive Grade BME MLCCs meet this requirement
- The formula described can be used as a simple rule of thumb when designing the BME MLCCs for high reliability applications
- It can also be used as an empirical criterion of construction analysis to reject a BME capacitor for high-reliability use prior to tedious life testing

Application Example(s): *R (t=0)* (Cont'd)

Number of Zeroes

$$R(t=0)=\left[1-\left(\frac{\bar{r}}{d}\right)^{\alpha}\right]^{N}=1.00000$$

TABLE V. Product level designator.		BX life to failure rate:	BX life to Reliability:
	➡	M: B1% life P: B0.1% life R: B0.01% life S: B0.001% life	M: B1% life $=\eta\cdot\{-ln[R(x_1\%)]\}^{1/\beta}$ where $R(x_1\%)$ =0.99 P: B0.1% life $=\eta\cdot\{-ln[R(x_2\%)]\}^{1/\beta}$ where $R(x_2\%)$ =0.999 R: B0.01% life $=\eta\cdot\{-ln[R(x_3\%)]\}^{1/\beta}$ where $R(x_3\%)$ =0.9999 S: B0.001% life $=\eta\cdot\{-ln[R(x_4\%)]\}^{1/\beta}$ where $R(x_4\%)$ =0.99999

TABLE V. Product level designator.

Symbol	Product level
C	non-ER
M	1.0 1/
P	0.1 1/
R	0.01 1/
S	0.001 1/

1/ FRL (percent per 1,000 hours).

MIL-PRF-55681, paragraph, 1.2.1.7

Number of zeroes represents the level of failure rate!

Note: Some dopants such as Ca, Mg etc. may function as grain growth prohibiters. This criterion must be used carefully and for apple-to-apple comparisons only!

Summary and Future Work

- A general reliability model for BME capacitors has been developed, which consists of three parts:
  - A 2-parameter Weibull distribution
  - Two acceleration functions:
    - a power-law form for catastrophic failures
    - an exponential-law form for slow degradation failures
  - An empirical function that defines contribution of the structural/constructional characteristics of a MLCC, such as the number of dielectric layers ***N***, dielectric thickness ***d***, average grain size $\bar{r}$.
  - The capacitor chip size *A* is found to not play a role in the reliability of a BME MLCC
- At *t=0* the reliability model can be used as a construction analysis selection criterion for BME MLCCs that may be applicable to high-reliability applications
- For future work
  - Work closely with manufacturers to verify/improve the reliability model
  - Significant amount of life testing of BME capacitors

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Thank you! Any Questions?